A NONPERTURBATIVE CALCULATION OF BASIC CHIRAL QCD PARAMETERS WITHIN ZERO MODES ENHANCEMENT MODEL OF THE QCD VACUUM. II

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Abstract

Basic chiral QCD parameters (the pion decay constant, quark and gluon condensates, the dynamically generated quark mass, etc) as well as the vacuum energy density have been calculated from first principles within a recently proposed zero modes enhancement (ZME) model of the QCD true vacuum. It is based on the solution to the Schwinger-Dyson (SD) equation for the quark propagator in the infrared (IR) domain. In order to analyze our numerical results we set a scale by the two different ways. First this was done at a scale responsible for dynamical chiral symmetry breaking (DCSB) at the fundamental quark level Λ_{CSBq}, defined as the double of the dynamically generated light quark mass m_d. In the second case m_d was reasonably taken to be $300 \leq m_d \leq 400$ (MeV) otherwise first remains arbitrary. Our unique input data was chosen to be the pion decay constant in the chiral limt given by the chiral perturbation theory at the hadronic level (CHPTh). With the help of the nonperturbative gluon contributions to the vacuum energy density one can establish realistic lower bounds for the m_d. In both cases we obtain almost the same numerical results for all chiral QCD parameters. Phenomenological estimates of these quantites are in good agreement with our numerical results. Also our numerical result for the vacuum energy density agrees well with the QCD sum rules and random instanton liquid model (RILM) values for this quantity. One of the most important our conclusions is that the above mentioned scale of DCSB at the fundamental quark level Λ_{CSBq} and the scale at which confinement occurs Λ_c are nearly the same indeed. Nonperturbative vacuum structure, which emerges from the ZME model, appears to be well suited to describe quark confinement, DCSB, the Goldstone nature of the pion, dimensional transmutation, etc on a general ground.

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I. INTRODUCTION

Let us begin the second part of our paper with the discussion of one of the most interesting feature of (dynamical chiral symmetry breaking) DCSB. As was underlined in the first part of our paper (hereafter Part I), there are only five independent quantities by means of which all other chiral QCD parameters must be calculated. For the sake of convenience, let us write down them together. They are:

$$F_{CA}^2 = \frac{3}{8\pi^2} k_0^2 z_0^{-1} \int_0^{z_0} dz \, \frac{z B^2(z_0, z)}{\{z g^2(z) + B^2(z_0, z)\}}, \tag{1.1}$$

$$m_d = k_0 \{z_0 B^2(z_0, 0)\}^{-1/2}, \tag{1.2}$$

$$\langle \overline{q} q \rangle_0 = -\frac{3}{4\pi^2} k_0^3 z_0^{-3/2} \int_0^{z_0} dz \, z B(z_0, z), \tag{1.3}$$

$$\epsilon_q = -\frac{3}{8\pi^2} k_0^4 z_0^{-2} \int_0^{z_0} dz \, z \left\{ \ln z \left[z g^2(z) + B^2(z_0, z) \right] - 2 z g(z) + 2 \right\}, \tag{1.4}$$

$$\epsilon_g = -\frac{1}{\pi^2} k_0^4 z_0^{-2} \times \left[18 \ln(1 + \frac{z_0}{6}) - \frac{1}{2} z_0^2 \ln(1 + \frac{6}{z_0}) - \frac{3}{2} z_0 \right], \tag{1.5}$$

where we recall that $g(z)$ and $B^2(z_0, z)$ are explicitly given by (1.14) and (1.15) of Part I. It is also instructive, along with the above, to write down definition (3.13) of Part I for the DCSB scale, namely

$$\Lambda_{CSBq} = 2 m_d. \tag{1.6}$$

So these final expressions which should be used to calculate chiral QCD parameters within our approach depend only on two independent quantities, namely: mass scale parameter k_0 and a constant of integration of dynamical quark SD equation of motion z_0. However, it follows from (1.2) that information on the parameter z_0 should be extracted again from m_d and the initial mass scale parameter k_0 itself, which characterizes the region where confinement, DCSB and other nonperturbative effects begin to play a dominant role (see below).

Despite the fact that in our treatment the initial mass scale parameter μ (characterizing the scale of nonperturbative effects) has been introduced by "hand" (see I), such a transformation of pair of independent parameters k_0 and z_0 into the pair of k_0 and m_d is also a direct manifestation of the phenomenon of the "dimensional transmutation" [1]. This phenomenon occurs whenever a massless theory acquires masses dynamically. It is a general feature of spontaneous symmetry breaking in field theories.

Let us emphasize once more that it is a general feature of our approach aiming at calculating all chiral QCD quantities numerically (those considered here and others as well) that one needs only two independent (free) parameters with clear physical sense. The above mentioned dynamically generated quark mass plays the role of the constant of integration of the corresponding equation of motion (the quark SD equation) instead of z_0 because of the above mentioned "dimensional transmutation" and mass scale parameter k_0 yields a scale at which important nonperturbative effects begin to play a dominant role. Our calculation scheme is self-consistent because we calculate $n = 5$ independent physical quantities by means of $m = 2$ free parameters having clear physical sense, so condition of self-consistensy $n > m$ is satisfied. The general behaviour of some of our parameters, in particular of the vacuum energy density due to nonperturbative gluon contributions and the pion decay constant given by the relations (1.5) and (1.1) are shown in Figs. 1, 2 and 3, respectively.

Our approach makes it possible to calculate all chiral QCD parameters (the ones considered here plus others) at any requested combination of m_d and k_0, but in order to analyse numerical results it is necessury to set a scale at which it should be done. We set a scale by the two, at first sight, different ways but leading (see below) to almost the same numerical results within our calculation scheme.

Evidently, to set a scale in each case makes it possible to determine only one of two free parameters in our calculations. In order to determine the second one we use the chiral value of the pion decay constant obtained by the Chiral perturbation theory at the hadronic level (CHPTh) in Ref. 2, namely

$$F^o_\pi = (88.3 \pm 1.1)\ MeV. \tag{1.7}$$

Exactly this value is chosen as an input data in our numerical investigation of chiral QCD. The pion decay constant is a suitable experimental number since it is directly measurable quantity as opposed, for example, to the with quark condensate or the pion-quark coupling constant. For this reason with our choice (1.7) as input data we may reliably estimate the deviation of the chiral values of physical quantities, which can not be directly measured, from their "experimental", phenomenologically determined values.

In the above mentioned CHPTh (or equvivalently the effective field theory) [3, 4] there is a low energy constant B, determined by

$$\langle \overline{q}q \rangle_0 = -F^2 B \tag{1.8}$$

and measures the vacuum expectation value of the scalar densities in the chiral limit. It is just this constant that determines the meson mass expansion in the general case. Indeed, in leading order (in powers of quark masses and e^2) from CHPTh, one has

$$M^2_{\pi^+} = (m^0_u + m^0_d)B \tag{1.9}$$

$$M^2_{K^+} = (m^0_u + m^0_s)B \tag{1.10}$$

$$M^2_{K^0} = (m^0_d + m^0_s)B. \tag{1.11}$$

Calculating independently the constant B from (1.8), one then will be able to correctly estimate current quark masses m^0_u, m^0_d and m^0_s using the experimental values of meson masses [5] in (1.9-1.11).

II. ANALYSIS OF THE NUMERICAL DATA AT A SCALE OF DCSB AT THE QUARK LEVEL

Let us begin by recalling that there exists a natural scale within our approach to DCSB. Indeed, at the fundamental quark level the chiral symmetry is spontaneously broken at a scale Λ_{CSBq} defined by (1.6). Therefore it makes sense to analyse our numerical data at a scale where DCSB at the fundamental quark level occurs. To this end, it is necessary only to simply identify mass scale parameter k_0 with this scale Λ_{CSBq}, i.e. to put

$$k_0 \equiv \Lambda_{CSBq} = 2m_d. \tag{2.1}$$

In other words, we will analyse our numerical results at a scale responsible for DCSB at the fundamental quark level. Evidently, this uniquely determines the constant of integration of the quark SD equation. Indeed, from (1.2) and on account of (2.1), then it immediately follows that this constant is equal to $z_0 = 1.34805$. From the pion decay constant in the chiral limit (1.7), chosen as input data, and on account of (1.1) and this value for z_0, from (2.1) it yields the numerical value for k_0 (see Table 1). This means that all physical parameters considered in our paper are uniquely determined. Results of our calculations are displayed in Table 1.

It is easily understandable within our approach that one can intrinsically compare the numerical results of different approches with each other. For example, of the CHPTh [2-4] with those of the QCD sume rules [6, 7] and vice versa. In the most simplest way, this can be done by setting a scale based on the exact definition (2.1) (calculation scheme A). One needs only to chose input data from the corresponding approach and then proceed as it was described above. now we do not present these calculations. Though here and in the next section it will be instructive to explicitly display our numerical results when the chiral value of the pion decay constant is approximated by the experimental value advocated in Refs. 8 and 9, namely $F^o_\pi = 92.42 \ MeV$, as well as by the standard value $F^o_\pi = 93.3 \ MeV$. For the above calculated parameters these results are also shown in Table 1.

Llet us make a few concluding remarks. To set a scale by the way described in this section has the advantage that it is based on the exact definition (2.1) for a scale of DCSB at which analysis of the numerical data must be done. In general, it is not obvious that this scale Λ_{CSBq} and scale Λ_c, at which quark confinement occurs, should be of the same order of magnitude. Moreover, the information about Λ_c is hidden within this scheme of calculation. In order to reveal the raison d'etre for Λ_c and its relation to Λ_{CSBq}, let us set a scale in the way described in the next section.

III. ANALYSIS OF THE NUMERICAL DATA AT THE CONFINEMENT SCALE

As wew noted above, in our approach there exists only one scale, denoted as μ or k_0 (separating, in general, the nonperturbative phase from the perturbative one), that is responsible for all the nonperturbative effects in QCD at large distances. If there is a close relation between quark confinement and DCSB (and we believe that this is so) then the scale of DCSB at the fundamental quark level (1.6) and the confinement scale Λ_c should be, at least, of the same order of magnitude. In other words, within our approach Λ_c should be very close to Λ_{CSBq}. This is in agreement with Monte Carlo simulations on the lattice which show that the deconfinement phase transition and the chiral symmetry restoring phase transition occur approximately at the same critical temparuture [10], confirming thereby the close intrinsic link between these nonperturbative phenomena.

Unfortunately, neither the exact value of m_d or k_0 is known. For this reason, let us first reasonably assume that the dynamically generated quark masses in any case should not be less than 300 MeV and should not exceed 400 MeV, i. e.

$$300 \leq m_d \leq 400 \ (MeV), \tag{3.1}$$

otherwise they remain arbitrary. We believe that this interval covers all possible realistic values used for and obtained in various numerical calculations. The second independent parameter k_0 be varied in the region of 1 GeV - the characteristic scale of low energy QCD. Varying independently these pairs of parameters m_d and k_0 numerically, one can calculate all chiral QCD parameters with the above derived formulae (1.1-1.5).

From the value of the pion decay constant in the chiral limit (1.7), as well as from the range selected first for m_d (3.1) and on account of (1.1) and (1.2), it follows that the momentum k_0 always should satisfy the upper and lower boundary value conditions, namely $691.32 \leq k_0 \leq 742.68 \ (MeV)$. The vacuum energy density which is due to nonperturbative gluons (1.5) changes its sign in the range selected for m_d (3.1) and in this interval for k_0. Therefore it becomes positive and this should not be so because of the normalization condition (we normalize perturbative vacuum to zero, see Part I). It is easy to show that this is result of that the lower bound chosen for the dynamical generated quark mass in (3.1) is too low. Indeed, the vacuum energy density (1.5) vanishes at the critical point $z_0^{cr} = 1.45076$ (see Fig. 1). Then from (1.2) calculated at this point, it follows that

$$k_0 \leq 2.26 m_d. \tag{3.2}$$

Using this ineqaulity in additional, the vacuum energy density (1.5) will always be negative as it should be and it will become zero only at critical values determined as $k_0^{cr} = 2.26 m_d$. From the chosen interval for m_d (3.1) and the obtained interval for k_0, however, it follows that the ratio between the corresponding lower bounds $k_0/m_d = 691.32/300 = 2.3044$ does not satisfy the above obtained inequality (3.2), while this ratio for the corresponding upper bounds $k_0/m_d = 742.68/400 = 1.8567$ satisfies it. This explicitly shows that the lower bound for m_d in (3.1) was incorrectly chosen. The exact lower bound for m_d can be found from the k_0^{cr} as $742.68 = 2.26 m_d$, and (3.1) becomes

$$328.62 \leq m_d \leq 400 \ (MeV). \tag{3.3}$$

In the range determined by (3.3) and in the above obtained interval for k_0, the vacuum energy density (1.5) will be always negative because any combination (ratio) of k_0 and m_d from these intervals will satisfy inequality (3.2). But this is not the whole story yet. A new lower bound for the m_d leads to a new lower bound for k_0 as well. Indeed, combine now this new lower bound (3.3) with the chiral value of the pion decay constant (1.7) and you obtain a new lower bound for k_0 as well.

As noted above, k_0 is regarded as a momentum which separates the nonperturbative phase (region) from the perturbative one. In the region obtained for k_0 the nonperturbative effects, such as quark confinement and DCSB, begin to play a dominant role. It is a region determining a scale at which confinement occurs. From now on let us call this scale for k_0

a confinement scale (in the chiral limit) and denote it Λ_c. So the final numerical values for the confinement scale are as follows

$$707 \leq \Lambda_c \leq 742.68 \ (MeV). \tag{3.4}$$

In intervals determined by (3.3) and (3.4) the vacuum energy density ϵ_g will be always negative (see Fig. 2).

It is worth noting that any value for Λ_c from interval (3.4) is possible but not any combination of Λ_c from interval (3.4) and m_d from interval (3.3) will automatically satisfy the value of the pion decay constant given by (1.7). Therefore it is necessary to adjust values of m_d from (3.3) for chosen value of Λ_c from interval (3.4) and vice versa (see Fig. 3). This means that m_d is in close relationship with Λ_c. Moreover, completing the above mentioned procedure, one finds that Λ_c is nearly the double of the generated quark mass m_d, i. e.

$$\Lambda_c \approx 2m_d. \tag{3.5}$$

This confirms that Λ_c and Λ_{CSBq} defined by (1.6) are nearly the same indeed. In the previous calculation scheme the adjusting procedure was automatically fulfilled because of the exact relation (2.1). Thus there is an intimate relationship between Λ_{CSBq} and Λ_c on the one hand and the double generated quark mass m_d on the other hand.

The nterval (3.4) for possible values of Λ_c along with the new range for m_d (3.3) will uniquely determine numerically the upper and lower bounds for all other chiral QCD parameters considered here. Like in the previous case, our numerical results are shown in Table 2 (calculation scheme B), where the shorthand $\langle 0|G^2|0\rangle$ stands for the gluon condensate $\langle 0|\frac{\alpha_s}{\pi}G^a_{\mu\nu}G^a_{\mu\nu}|0\rangle$. Our numerical bounds for the vacuum energy density ϵ need additional remarks. We note that the bounds for ϵ is not the sum of bounds for ϵ_q and ϵ_g. The upper and lower bounds for ϵ_q are achieved at the upper and lower bounds for m_d (Λ_c) while for ϵ_g they are achieved at the lower and upper bounds of m_d (Λ_c). At the same time true intervals for ϵ differ very little from each other in each considered case (see Table 2).

Let us now prove the relation (3.5). We have already learnt known that correct values of k_0 belong to the interval for Λ_c (3.4). Then identifying k_0 with the Λ_c in (3.2), one obtains

$$\Lambda_c \leq (2 + 0.26) m_d = \Lambda_{CSBq} + 0.26 m_d, \tag{3.6}$$

so

$$\Delta = \pm(-1 + \frac{\Lambda_c}{\Lambda_{CSBq}}) \leq 0.13, \tag{3.7}$$

where the positive sign corresponds to $\Lambda_c > \Lambda_{CSBq}$ and the negative one is valid when $\Lambda_c < \Lambda_{CSBq}$. In derivation of both relations we used definition (1.6). The maximum deviation will be achievied only at the critical point when contribution to the vacuum energy density due to nonperturbative gluons vanishes. Of course, this is not the case and these two scales are very close indeed to each other.

To conclude, it is worth underlining once more that besides good numerical results obtained in this section, we have established the existence of realistic lower bound for the dynamically generated quark masses. In each calculated case their numerical values are shown in Table 2. Thus one concludes that the vacuum energy density due to nonperturbative gluons is sensitive to the lower bound for m_d. The second important result is that we have clearly shown that the confinement scale Λ_c and DCSB scale Λ_{CSBq} are nearly the same indeed.

IV. CONCLUSIONS

Let us briefly compare our numerical results obtained from first principles with phenomenologically estimated values of the physical parameters considered here. An estimate of the quark condensate in Refs. 7 and 6,

$$\langle \overline{q} q \rangle_0^{1/3} = -(225 \pm 25) \ MeV \tag{4.1}$$

is in good agreement with our values. It is worth noting here that QCD sum rules give usually the numerical values of physical quantities, in particular the quark condensate, approximately within an accuracy of (10-20)% (see, for example Ref. 11).

Our values for the current quark masses are also in good agreement with recent estimates from hadron mass splittings [12]

$$m_u^0 = (5.1 \pm 0.9)\ MeV,$$

$$m_d^0 = (9.0 \pm 1.6)\ MeV,$$

$$m_s^0 = (161 \pm 28)\ MeV \tag{4.2}$$

and QCD sum rules [13]

$$m_u^0 = (5.6 \pm 1.1)\ MeV,$$

$$m_d^0 = (9.9 \pm 1.1)\ MeV,$$

$$m_s^0 = (199 \pm 33)\ MeV, \tag{4.3}$$

see also reviews [14]. It is interesting to note that agreement of our values (Table 1) with the QCD sum rules values (4.3) is slightly better than with those of (4.2) obtained from hadron mass splittings.

Here it is worth mentioning that from our numerical results (Tables 1 and 2) it follows that the constituent quark mass m_q should differ little from m_d. Apparently, the difference between them is of order (1-3)% only from the displayed values of m_d and is negligible for heavy quarks. So without making a big mistake even for light quarks, it is possible to simply use m_d instead of m_q. Doing so one comes to the conclusion that CHPTh with (1.7) and the constituent quark model (CQM) with the value for the constituent quark mass $m_q = 362\ MeV$ advocated by Quigg [15] are nearly in one-to-one correspondence within our calculation scheme (see Table 1). Moreover, from our numerical results (Tables 1 and 2) one can conclude that the dominant contributions to the values of all chiral QCD parameters as well as the vacuum energy density come from large distances, while the contributions from the short and intermediate distances can only be treated as small perturbative corrections.

The phenomenological analysis of the QCD sum rules [7] for the numerical value of the gluon condensate implies

$$\langle 0 | \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^a_{\mu\nu} | 0 \rangle \simeq 0.012\ GeV^4, \tag{4.4}$$

and using then again (2.5) of Part I, one obtains the vacuum energy density as

$$\epsilon \simeq -0.003375 \ GeV^4. \tag{4.5}$$

In the random instanton liquid model (RILM) [16] of the QCD vacuum, for a dilute ensemble, one has

$$\epsilon = -\frac{9}{4} \times 1.0 \ fm^{-4} \simeq -0.003411 \ GeV^4. \tag{4.6}$$

The estimate of the gluon condensate within the QCD sum rules approach can be changed within a factor of two [7]. We trust our numerical results for the vacuum energy density much more than those of the gluon condensate. The former was obtained on the basis of the completely nonperturbative ZME model of the vacuum of QCD while the latter was obtained on account of the perturbative solution for the CS-GML β-function [7]. In order to realiably calculate the gluon condensate, it is necessary to calculate the CS-GML β-function within the nonperturbative ZME model of quark confinement and DCSB. This calculation is not straightforward and will be performed elsewere. Let us also emphasize that important fact that our calculation of the vacuum energy density is a calculation from first principles while in the RILM [16] the parameters characterizing vacuum, the instanton size $\rho_0 = 1/3 \ fm$ and the "average separation" $R = 1.0 \ fm$ were chosen to precisely reproduce traditional (phenomenologically estimated from the QCD sum rules) values of quark and gluon condensates, respectively.

The remarkable feature of our calculation is that we did not take into account instanton-like fluctuations at all. However, we reproduce values (4.4-4.6), which are due to the instanton-type fluctuations only, especially well when the pion decay constant in the chiral limit was approximated by its experimental value. Moreover, our numerical results clearly show that the contribution to the vacuum energy density of the confining quarks with dynamically generated masses ϵ_q is approximately equal to ϵ_g, that is of the nonperturbative gluons. At the same time, it is well known that in the chiral limit (massless quarks) tunneling is totally suppressed, i.e. the contribution of the instanton-type fluctuations to the vacuum energy density vanishes. It will be restored again in the presence of DCSB [17-19]. Thus, in principle, in the chiral limit and in the presence of DCSB, the total vacuum energy density should be the sum of these three quantities, i.e. $\epsilon_t = \epsilon_q + \epsilon_g + \epsilon_{I\bar{I}}$, where $\epsilon_{I\bar{I}}$ is due to the instanton-antiinstanton interactions.

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TABLE I. Calculation scheme A

F_π^0	88.3	92.42	93.3	MeV
Λ_{CSBq}	724.274	758.067	765.284	MeV
m_d	362.137	379.0335	382.642	MeV
$\langle\overline{q}q\rangle_0$	$(-208.56)^3$	$(-218.29)^3$	$(-220.36)^3$	MeV^3
ϵ_q	-0.0012	-0.00143	-0.0015	GeV^4
ϵ_g	-0.0013	-0.00157	-0.0016	GeV^4
ϵ	-0.0025	-0.0030	-0.0031	GeV^4
$\langle 0\vert\frac{\alpha_s}{\pi}G^a_{\mu\nu}G^a_{\mu\nu}\vert 0\rangle$	0.009	0.0106	0.011	GeV^4
B	1163.51	1217.78	1229.23	MeV
m_u^0	6.65	6.36	6.30	MeV
m_d^0	10.08	9.63	9.54	MeV
m_s^0	202.85	193.75	191.94	MeV

TABLE II. Calculation scheme B

$F_\pi^o = 88.3$	$F_\pi^o = 92.42$	$F_\pi^o = 93.3$
$707 \le \Lambda_c \le 742.68$	$737.9 \le \Lambda_c \le 768.4$	$744.4 \le \Lambda_c \le 773.86$
$328.62 \le m_d \le 400$	$340 \le m_d \le 400$	$342.416 \le m_d \le 400$
$(-210.34)^3 \le \langle \overline{q}q \rangle_0 \le (-206.9)^3$	$(-219.3)^3 \le \langle \overline{q}q \rangle_0 \le (-216.34)^3$	$(-221.2)^3 \le \langle \overline{q}q \rangle_0 \le (-218.33)^3$
$-0.00135 \le \epsilon_q \le -0.00096$	$-0.0016 \le \epsilon_q \le -0.00128$	$-0.0017 \le \epsilon_q \le -0.00136$
$-0.0024 \le \epsilon_g \le -0.00045$	$-0.00226 \le \epsilon_g \le -0.00044$	$-0.00221 \le \epsilon_g \le -0.000437$
$-0.00336 \le \epsilon \le -0.0018$	$-0.00354 \le \epsilon \le -0.002$	$-0.00356 \le \epsilon \le -0.0021$
$0.0064 \le \langle 0\|G^2\|0\rangle \le 0.0128$	$0.007 \le \langle 0\|G^2\|0\rangle \le 0.0192$	$0.00746 \le \langle 0\|G^2\|0\rangle \le 0.0199$
$1135.95 \le B \le 1193.56$	$1185.44 \le B \le 1234.76$	$1195.57 \le B \le 1243.34$
$6.48 \le m_u^0 \le 6.81$	$6.27 \le m_u^0 \le 6.53$	$6.22 \le m_u^0 \le 6.47$
$9.83 \le m_d^0 \le 10.33$	$9.5 \le m_d^0 \le 9.89$	$9.43 \le m_d^0 \le 9.81$
$197.67 \le m_s^0 \le 207.7$	$191 \le m_s^0 \le 199$	$189.76 \le m_s^0 \le 197.34$

FIGURES

FIG. 1. The vacuum energy density due to nonperturbative gluons contributions (1.5) as a function of z_0.

FIG. 2. The vacuum energy density due to nonperturbative gluons contributions (1.5) as a function of k_0. Λ_c is the confinement scale. For details see section 3. A similar figure can be drawn for the case when the pion decay constant is approximated by the experimental value.

FIG. 3. The pion decay constant F_{CA} as function of k_0. Λ_c is the confinement scale. A similar figure can be drawn for the case when the pion decay constant is approximated by the experimental value.